88-Inch Cyclotron Operations Overview

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Introduction

The 88-Inch Cyclotron is operated as a national facility in support of U.S. Department of Energy programs in basic nuclear science. The central component is a sector-focused, variable-energy cyclotron that can be fed by either of two Electron Cyclotron Resonance (ECR) ion sources. This versatile combination produces heavy-ion beams of elements throughout the periodic table. For helium to oxygen, beam energies are up to 32.5 MeV/nucleon; for heavier ions the maximum energy per nucleon decreases with increasing mass. Typical ions and maximum energy (MeV/nucleon) are argon (23), krypton (14), xenon (8) and bismuth (5). Most metallic ions and all gaseous ions up to mass 170 have either been accelerated or can be developed as needed, with energies high enough for nuclear physics studies. High intensity light ions - p, d, ^{3}He and ^{4}He - are produced up to total energies of 55, 65, 135, and 130 MeV, respectively.

Accelerator Use

FY99 was a productive and exciting year for the 88-Inch Cyclotron. The Berkeley Gas-Filled Separator (BGS) came into operation early in FY99, providing new and exciting research opportunities. The discovery of the superheavy elements 116 and 118 using the BGS was the highlight of the year. The 8-Pi Spectrometer was utilized at full capacity and attracted many outside users to perform nuclear structure experiments not requiring the power of Gammasphere. Towards the end of FY99, BEARS provided the first radioactive ^{11}C beams for experiments, attracting new outside users in nuclear astrophysics and reactions. The research time (beam on target) in FY99 was 4519 hours, an increase of approximately 15% from FY98 levels. The Accelerator Operation Summary (Table 1) shows that in FY99 75% of the scheduled time was used for research (beam on target) while the remaining time was divided between tuning (15%), machine studies (5%), and unscheduled maintenance (5%).

Nuclear science research accounted for 3694 research hours, applied research for 519 hours, high energy physics for 236 hours, and biology for 70 hours. Two-thirds of the nuclear science research utilized one of the three new facilities: the 8-Pi Spectrometer (40%), BGS (25%) and BEARS (2%). The nuclear science research can be broken down into nuclear structure (44%), heavy elements and chemistry (35%), exotic nuclei (9%), reactions (8%), astrophysics (2%) and weak interactions (2%). The applied research - in partnership with both U.S. and foreign industry, small business, and government laboratories - consisted primarily of radiation effects testing for space applications. The research for high energy physics was done in support of the development of detectors and associated electronics for the ATLAS detector at LHC. The biology research was done primarily in support of the NASA NSCORT program.

Ions, Energies and Intensities

The cyclotron fed by its ECR sources provides a wide range of ions, energies, and intensities and most elements can be accelerated. To date, 48 elements have been accelerated including every element from hydrogen to zinc. The heaviest element accelerated is uranium. Figure 1 gives a Chart of the Nuclides of 88" beams and their corresponding intensities at 5 MeV/u. A total of 98 isotopes have been accelerated - recent additions are ^{43}Ca, ^{87}Rb, ^{94}Zr, ^{97,98,100}Mo and ^{127}I. Many ions have been run using isotopically enriched source materials including ^{3}He, ^{13}C, ^{15}N, ^{18}O, ^{21,22}Ne, ^{25,26}Mg, ^{33,34,36}S, ^{44,48}Ca, ^{64}Ni, ^{70}Ge, ^{78,86}Kr, ^{96}Zr, ^{136}Xe, and ^{154}Sm. Figure 2 shows the beams actually run at the 88-Inch in FY99. 25% of the beam time used light ions ($Z< 4$).

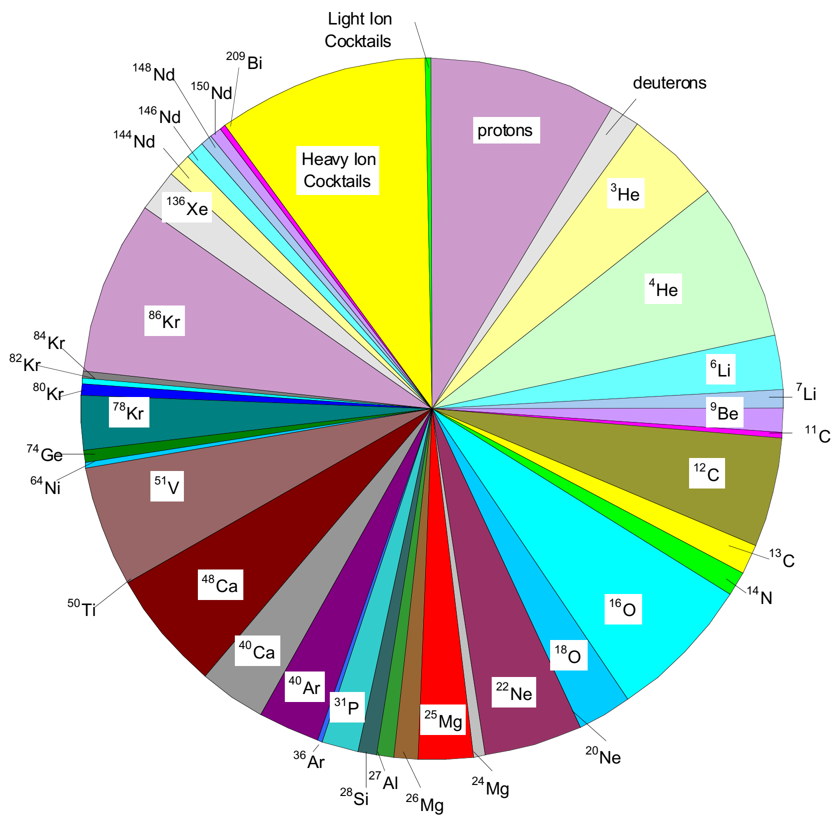
Development projects in recent years have focused on increasing the intensity of medium to heavy mass beams both out of the ECR source (AIP 19xx) and through the Cyclotron (AIP 19xx). These projects proved crucial to the discovery of Elements 116 and 118. At the present time, the 88" Cyclotron is the only U.S. accelerator capable of generating the several hundred particle-nanoamp beams of ^{86}Kr necessary for this discovery. Development is in progress towards other high intensity heavy beams which might prove useful in cold fusion searches for superheavy elements, including ^{87}Rb and even heavier beams such as Xe or Te.

Advances in the technology of producing integrated circuits have led to new requirements for the beams necessary to perform radiation effects testing; namely that the beams have enough energy to penetrate a layer of material on top of the active part of the device. This demand for beams with higher range have led to development of a "cocktail" beam of 10 MeV/nucleon to supplement the 4.5 MeV/nucleon beam presently used for radiation effects testing. This new cocktail beam has enjoyed increasing use in recent months, and has attracted a community of users from Europe as well as the United States.

Additional improvements underway by the ECR Ion Source group include:

1. new miniature ovens to further increase the flexibility of the ion sources for metal ion beam production,
2. a new emittance scanner device to investigate the ion-optical parameters of the AECR-U injection beam line at higher beam-current densities, leading to improved ion beam transmission, and
3. investigation of cyclotron injection at higher voltages, replacement of beam line components and improved diagnostics in the central region of the Cyclotron.

Figure 2. FY99 Beams



VENUS

A new very high magnetic field superconducting ECR ion source, called VENUS (Versatile ECR Ion Source for Nuclear Science) is under development at the cyclotron. It will boost the maximum energies and intensities for heavy ions from the cyclotron. The design and fabrication of the magnet structure is based on a joint effort between the 88-Inch Cyclotron of the Nuclear Science Division and the Supercon Group in the Accelerator and Fusion Research Division at Lawrence Berkeley National Laboratory.

The magnet structure of the ion source consists of three solenoids and six racetrack coils with iron poles forming the sextupole. The coils are designed to generate a 4T axial mirror field at injection and 3T at extraction and a radial sextupole field of 2.4 T at the plasma chamber wall. A novel concept for mechanical pre-loading of the sextupole assembly has been developed to allow operation of the sextupole in the high magnetic solenoid field. The sextupole and solenoid assembly has been successfully cold tested fall of 1999. The solenoid coils have never initiated quenching, and the sextupole coils trained rapidly to fields above the design requirements. This magnet structure will allow operating the VENUS ECR ion source at the magnetic fields greater than any source now operating.

The design of the horizontal cryostat and iron yoke for the magnet structure will be completed March 00. Force calculations including the iron yoke have been performed to design the cold-mass support. The cryostat will be constructed in FY2000.

The mechanical design of the conventional ion source components, the beam line and mass analyzing system is underway and will be completed spring 2000. The construction and assembly of the ion source has already been initiated by preparing the site on top of the cyclotron roof. The completion of the new beam line, which will include one Glaser lens, four quadrupoles and two bending magnets, is planned in fall 2001 allowing first beam injection into the cyclotron.

Radioactive Beam Technology

The two radioactive ion beam (RIB) initiatives at the 88-Inch Cyclotron -- BEARS (**B**erkeley **E**xperiments with **A**ccelerated **R**adioactive **S**pecies) and the production of ^{14}O for tests of the Standard Model -- depend on reliable and high performance ECR ion sources.

In the best case experimental runs for BEARS, ^{11}C beam intensities of about $2x10^9$ $^{11}C^{4+}$ ions/sec were extracted. from the AECR-U ion source. This corresponded to an intensity of up to $2x10^8$ particles/sec of fully stripped (in order to eliminate contamination from ^{11}B) ions on target. The final beam intensity is very dependent on the charge state extracted from the source, the energy of the accelerated beam and the transmission of the beam line. Predicted and achieved intensities on target for ^{11}C beams for BEARS experiments are shown in Figure 3. ^{14}O beams for BEARS are under development. The best beam intensity for ^{14}O is predicted to only be $1\text{-}2x10^6$ due to the much shorter half-life

(70 sec). Improvements in beam diagnostics for RIB runs will be needed in order to efficiently tune these low intensity beams.

The ^{14}O experiment is a joint effort of the Weak Interaction Group in NSD and 88 Operations. For this experiment the new 6.4 GHz ECR ion source IRIS (**I**on **S**ource for **R**adioactive **Is**otopes) was developed. The source started operation this spring and is used for the ionization of ^{14}O. The primary goal of this ion source is the efficient on-line production of a $^{14}O^{+}$ ion beam to measure the shape spectrum of the ^{14}O beta-decay. ^{14}O is generated in the form of CO in a high temperature carbon target using a 20 MeV $^{3}He^{+}$ beam from the LBNL 88" Cyclotron via the reaction $^{12}C(^{3}He,n)^{14}O$. The CO is disassociated and the ^{14}O is ionized in IRIS. An analyzing magnet separates the ^{14}O beam from other activity and is then implanted into a thin carbon foil. This minimizes the radiation background and maximizes the signal in the beta spectrometer by concentrating the ^{14}O sample size. In the first test runs $^{14}O^{+}$ of up to 2 10^{6} particles/sec have been achieved. These ^{14}O ion beam intensities are among the highest achieved of any radioactive ion beam facility today. Careful optimization of the ion source efficiency is underway and systematic ionization efficiency measurements have begun.

Using LDRD money, an effort has begun to develop mid-mass long-lived RIBs for structure studies using the Cyclotron to both produce and accelerate the radioactive species - a so-called "recyclotron". Initial development is focused on ^{76}Kr and ^{79}Kr, two species of interest for nuclear structure studies. Production rates are under study using proton and He induced reactions.

Figure 3. ^{11}C Intensity

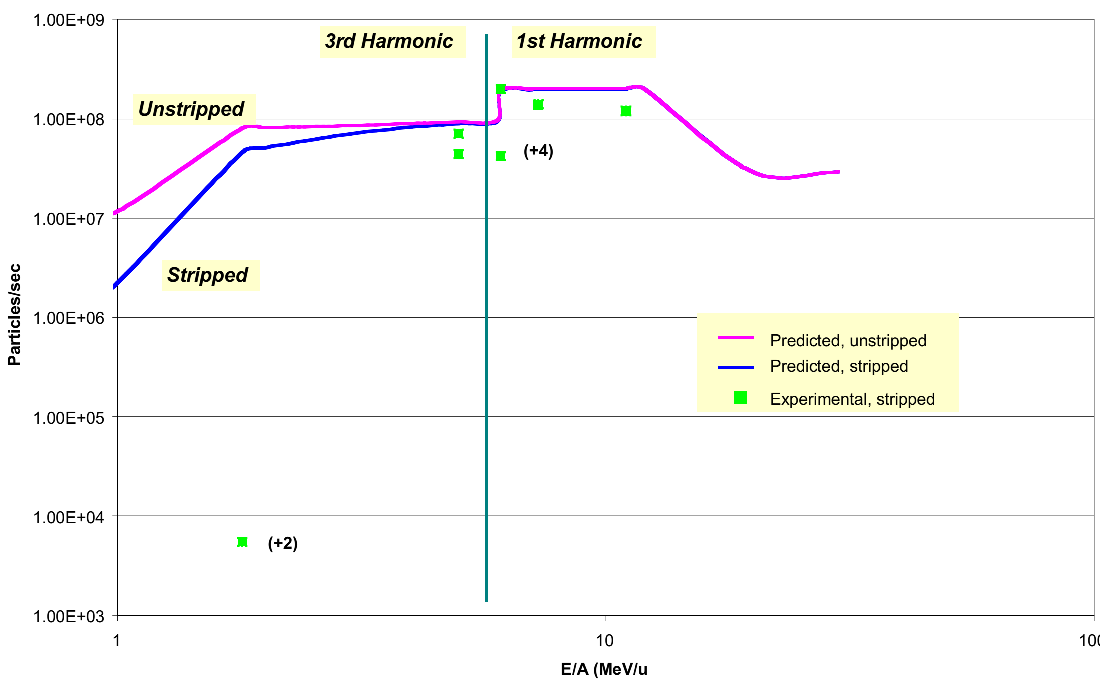


Table 1
Accelerator Operation Summary - FY99

Accelerator Operation Summary (hours)	
Research	4519
Tuning	895
Machine Studies	326
Unscheduled Shutdowns	285
Scheduled Shutdowns	2735
Electrical Energy Consumption (GWH)	4.3
Cost of Electrical Energy (Thousands of Dollars)	311
Financial Support for Accelerator Facility	
Operation (Thousands of Dollars)	
Heavy Ion Physics (KB-02-02)	3852
Biomedical and Environmental Research	0
Other Sources	413
Total	4265
Experiment Summary	
Beam Utilization for Research (Hours)	
Nuclear Research	3694
Atomic Physics	0
Biology and Medicine	70
High Energy Physics	236
Applied Research (recharge)	519
Total	4519
Nuclear Science Research	
Number of Nuclear Science Experiments	76
Number of Scientists Participating	109
Number of Students	20
Institutions Represented	
Universities	9
DOE National Laboratories	5
Foreign Institutions	15
Other government labs	0
Non-nuclear Science Research	
Number of scientists and engineers	69
Number of students	2
Institutions and Companies	15
Total users (all research)	200
Percentage of Beam Time (all research)	
In-House Staff	54
Universities	14
DOE/Government Laboratories	6
Industry	11
Foreign Institutions	15